

Positron annihilation as a cosmic-ray probe

Yutaka Ohira^{1*}, Kazunori Kohri¹ and Norita Kawanaka²

¹*Theory Center, Institute of Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba 305-0801, Japan*

²*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

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ABSTRACT

Recently, the gamma-ray telescopes *AGILE* and *Fermi* observed several middle-aged supernova remnants (SNRs) interacting with molecular clouds. A plausible emission mechanism of the gamma rays is the decay of neutral pions produced by cosmic ray (CR) nuclei (hadronic processes). However, observations do not rule out contributions from bremsstrahlung emission due to CR electrons. TeV gamma-ray telescopes also observed many SNRs and discovered many unidentified sources. It is still unclear whether the TeV gamma-ray emission is produced via leptonic processes or hadronic processes. In this Letter, we propose that annihilation emission of secondary positrons produced by CR nuclei is a diagnostic tool of the hadronic processes. We investigate MeV emissions from secondary positrons and electrons produced by CR protons in molecular clouds. The annihilation emission of the secondary positrons from SNRs can be robustly estimated from the observed gamma-ray flux. The expected flux of the annihilation line from SNRs observed by *AGILE* and *Fermi* is sufficient for the future Advanced Compton Telescope to detect. Moreover, synchrotron emission from secondary positrons and electrons and bremsstrahlung emission from CR protons can be also observed by the future X-ray telescope NuSTAR and ASTRO-H.

Key words: acceleration of particles – cosmic rays – supernova remnants.

1 INTRODUCTION

The origin of cosmic rays (CRs) is a longstanding problem in astrophysics. Supernova remnants (SNRs) are thought to be the origin of Galactic CRs. The most popular SNR acceleration mechanism is diffusive shock acceleration (e.g. Blandford & Eichler 1987). In fact, *Fermi* and *AGILE* show that middle-aged SNRs ($\sim 10^4$ yrs old) interacting with molecular clouds emit GeV gamma rays with broken power law spectra (e.g. Abdo et al. 2009, 2010; Tavani et al. 2010; Giuliani et al. 2011) (Hereafter, these references are referred to as OBS). Considering a stellar wind before the supernova explosion, the molecular cloud has been swept away by the stellar wind. The inner radius of the molecular cloud becomes typically about a few tens of parsecs. Then, the SNR collides with the molecular cloud at typically 10^4 yrs later and the broken power law spectra of GeV gamma rays can be interpreted as the inelastic collision between molecular clouds and CR nuclei that have escaped from the SNR (hadronic processes) (Ohira, Murase & Yamazaki 2011a). However, observations do not rule out contributions from bremsstrahlung emission due to CR electrons (leptonic processes). SNRs have been also observed by TeV gamma-ray telescopes, and it is still unclear whether the

TeV gamma-ray emission is produced via inverse Compton scattering of CR electrons (leptonic processes) or hadronic processes. There are many TeV-unID sources in our galaxy, and their emission mechanisms are also still unclear. Old or middle-aged SNRs are the candidates of the TeV-unID sources (Yamazaki et al. 2006; Ohira et al. 2011b). Thus, it is crucial to identify the emission mechanism of gamma rays. Positrons and neutrinos are produced in hadronic processes. On the other hand, they are not produced in leptonic processes.¹ Therefore, direct or indirect detections of these particles will enable us to identify the emission mechanism in gamma-ray sources.

Recently, the CR positron excess has been provided by PAMELA (Adriani et al. 2008). Although the origin of this excess has been investigated in many theoretical studies (Kashiyama et al. 2011; Kawanaka et al. 2010; Ioka 2010, and references therein), it still remains unclear. SNRs have been discussed as the candidates of the positron sources (Fujita et al. 2009a; Blasi 2009; Shaviv, Nakar & Piran

¹ Strictly speaking, leptonic processes can produce positrons via $e^- + \gamma \rightarrow e^- + e^- + e^+$ but this reaction rate is suppressed by the fine structure constant compared with the gamma-ray production rate of inverse Compton scattering.

* E-mail: ohira@post.kek.jp

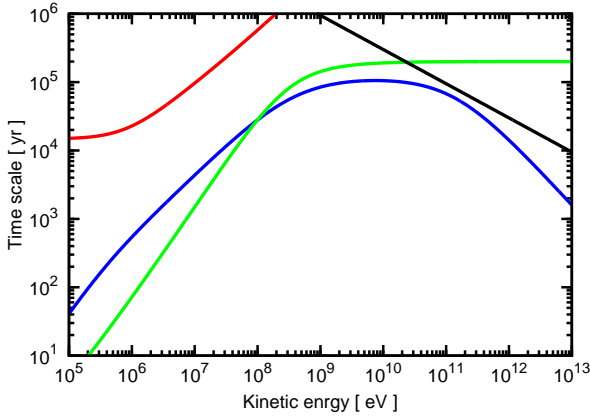


Figure 1. Timescales of interaction for CRs in a molecular cloud with the number density $n = 300 \text{ cm}^{-3}$, the size $R_c = 30 \text{ pc}$ and the magnetic field $B = 30 \mu\text{G}$. The blue and green lines show the cooling times of secondary positrons (and electrons) and CR protons, respectively. The red line shows the annihilation time of positrons. The black solid line shows the diffusion time with $\chi = 0.01$.

2009; Biermann et al. 2009; Mertsch & Sarkar 2009). Hence, it is important to observe the positron production at SNRs.

Gamma-ray telescopes showed that the photon flux above 100 MeV from SNRs with an age of about 10^4 yr is $F_{>100 \text{ MeV}} = \int_{100 \text{ MeV}}^{\infty} dE (dF/dE) = 10^{-7} - 10^{-6} \text{ photon s}^{-1} \text{ cm}^{-2}$ (OBS). If the gamma rays have a hadronic origin, about the same numbers of positrons are produced. When those positrons lose their energy sufficiently, about 80 percent of them would make positronium with ambient electrons, and one fourth of them would decay into two photons with the energy of 511 keV (e.g. Prantzos et al. 2010). This means that we can expect the 511 keV photon flux of the order of $10^{-8} - 10^{-7} \text{ photon s}^{-1} \text{ cm}^{-2}$. This flux is sufficiently high for five-years observations of the future Advanced Compton Telescope (ACT) to detect.

In this Letter, considering the interaction between CR protons and molecular clouds, we estimate annihilation emission of secondary positrons produced by the CR protons. We partly refer to analyses of previous works concerning the 511 keV line from the Galactic center (Agaronyan & Atoyan 1981; Beacom & Yüksel 2006; Sizun, Cassé & Schanne 2006) and the Galactic plane (Stecker 1967, 1969), and we apply their treatments to middle-aged SNRs interacting with molecular clouds. Recent review of positron annihilation can be found in Prantzos et al. (2010).

We first provide some timescales for CR protons, secondary positrons and electrons inside a molecular cloud (Section 2). We then solve energy spectra of the secondary positrons and electrons (Section 3) and calculate the annihilation line flux as well as the continuum spectrum (Section 4). Section 5 is devoted to the discussion.

2 RELEVANT TIMESCALES

In this section, we briefly summarize relevant timescales of CRs in a molecular cloud. Physical quantities of molecular clouds associated with gamma-ray sources have not been understood in detail. Observations suggest that the gas number density is about $n = 10^2 - 10^3 \text{ cm}^{-3}$, the size is of the order of 10 pc (OBS), and the magnetic field in molecular clouds is about $B = 1 - 100 \mu\text{G}$ (Crutcher et al. 2010). In this Letter, for the molecular cloud we adopt values of the gas number density $n = 300 \text{ cm}^{-3}$, the size $R_c = 30 \text{ pc}$ and the magnetic field $B = 30 \mu\text{G}$. We consider ionization and inelastic collisions with nuclei as cooling processes of CR protons. On the other hand, we include ionization, bremsstrahlung, synchrotron emission, and inverse Compton scattering with the cosmic microwave background (CMB) as cooling processes of secondary positrons and electrons. For SNRs observed by *Fermi* and *AGILE*, SNRs interact with molecular clouds and the expansion of the SNRs is strongly decelerated. Therefore, we here do not consider the adiabatic cooling.

We here define $\tau_{\text{cool}} = E/\dot{E}$ as a cooling time, where E and \dot{E} are the kinetic energy and the energy loss rate, respectively. We adopt an expression of \dot{E} for protons given in Mannheim & Schlickeiser (1994), and that for positrons and electrons given in Strong & Moskalenko (1998). The timescale of direct annihilation of positrons and electrons is represented by

$$\tau_{a,\pm}(E) = \frac{1}{n_{\mp}\sigma_a(E)v(E)}, \quad (1)$$

where n_{\pm} , σ_a and v are the number density of positrons or electrons, the cross section of the annihilation (Dirac 1930) and the velocity of secondary electrons or positrons, respectively. The electron density, n_- , is dominated by thermal electrons and the positron density, n_+ , is very small, so that we can neglect the annihilation of secondary electrons.

The escape time through diffusion is written by

$$\tau_d(E) = \frac{R_c^2}{4D(E)}, \quad (2)$$

where $D(E)$ is the diffusion coefficient. It is notable that so far the diffusion coefficient around an SNR has not been understood well. Thus we assume the diffusion coefficient in molecular clouds to be

$$D(E) = 10^{28} \chi \frac{v(E)}{c} \left(\frac{E}{10 \text{ GeV}} \right)^{0.5} \text{ cm}^2 \text{ s}^{-1}, \quad (3)$$

where c is the velocity of light. Here $\chi = 1$ might be reasonable as the Galactic mean value (Berezinskii et al. 1990), but $\chi = 0.01$ should be preferred in surroundings of SNRs (Fujita et al. 2009b, 2010; Torres et al. 2010; Li & Chen 2010), so that we use $\chi = 0.01$ in this Letter.

In Fig. 1 we show those relevant timescales. The blue line shows the cooling time of secondary electrons and positrons where the synchrotron cooling dominates above 100 GeV, the bremsstrahlung cooling dominates from 1 GeV to 100 GeV, and the ionization loss dominates below 1 GeV. The green line shows the cooling time of CR protons where the pion production cooling dominates above 1 GeV and the ionization loss dominates below 1 GeV. CR protons (about 1 GeV) producing most positrons do not cool and escape as long as the SNR age is smaller than the cooling time of 1 GeV protons. Cooling times of ionization, bremsstrahlung

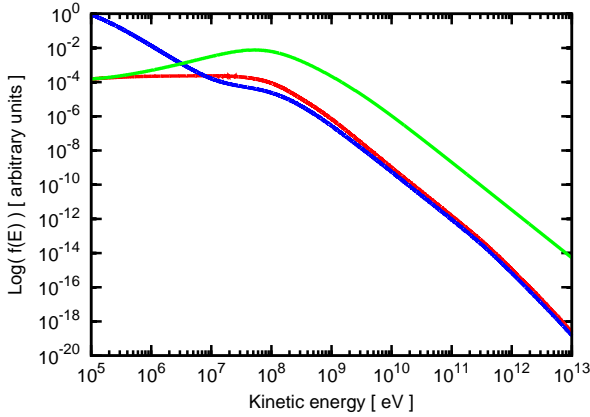


Figure 2. Energy spectra of CR protons, secondary positrons and electrons for $s = 2.8$ and $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$. The green, red and blue lines show CR protons, secondary positrons and electrons spectra, respectively.

emission and inelastic collision are inversely proportional to the gas density. Therefore, spectral evolutions of all CRs below 1 GeV depends on only the density. The black line shows the escape time due to diffusion with $\chi = 0.01$. The escape of secondary electrons and positrons is negligible compared with the energy loss.

The typical energy of positrons produced by the CR protons is about $E_t \sim 100 \text{ MeV}$ (Murphy 1987). Then its cooling time is about $3 \times 10^4 (n/300 \text{ cm}^{-3})^{-1} \text{ yr}$. Therefore, SNRs with an age longer than its cooling time can produce low energy positrons. Once positrons have cooled to 100 eV, they form positroniums through charge exchange. There are four possible spin configurations of the positroniums. One of them has the total spin 0 (singlet) and the three others have the total spin 1 (triplet). The singlet state produces 511 keV line photons, and the triplet state produces continuum photons below 511 keV. Because both the singlet and the triplet state are produced at the same rate, one fourth of positroniums can decay into two 511 keV line photons.

It is remarkable that the annihilation time is approximately 10 times longer than the cooling time of positrons at around 10 – 100 MeV. Then while the positron is being cooled, approximately 10–20 percent of positrons directly annihilate with electrons. They produce continuum photons above 511 keV.

3 ENERGY SPECTRA OF SECONDARY POSITRONS AND ELECTRONS

In this section, to calculate the photon spectrum from secondary positrons and electrons produced by CR protons, we calculate energy spectra of positrons and electrons, $f_{\pm}(t, E)$. An evolution of CR spectra is described by

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial E} (\dot{E}(E)f) + \frac{f}{\tau_a(E)} + \frac{f}{\tau_d(E)} = Q(t, E) , \quad (4)$$

where $Q(t, E)$ is the source term of CRs, the third and the fourth terms of the left hand side are sink terms due to annihilation and diffusion, respectively. As shown in Fig. 1, the diffusion escape for secondary electrons and positrons is

negligible, so that we neglect the diffusion escape. Then the solution for secondary positrons and electrons, f_{\pm} , can be expressed by

$$f_{\pm}(t, E) = \frac{1}{|\dot{E}(E)|} \int_E^{E_0(t, E)} d\epsilon Q_{\pm}(t', \epsilon) \times \exp \left(- \int_E^{\epsilon} \frac{d\epsilon'}{\tau_{a, \pm} |\dot{E}|} \right) , \quad (5)$$

where t' is time for cooling from E_0 to ϵ , and defined by

$$t' = \int_{\epsilon}^{E_0} \frac{d\epsilon'}{|\dot{E}(\epsilon')|} = t - \int_E^{\epsilon} \frac{d\epsilon'}{|\dot{E}(\epsilon')|} , \quad (6)$$

and $E_0(t, E)$ is the initial energy of positrons or electrons before they cool to E and defined by

$$\int_E^{E_0} \frac{d\epsilon}{|\dot{E}(\epsilon)|} = t . \quad (7)$$

We can neglect the annihilation loss for secondary electrons because the timescale is much longer than the SNR age.

Using the code provided by Kamae et al. (2006); Karlsson & Kamae (2008), we calculate secondary positrons and electrons source spectra, Q_{\pm} , and the gamma-ray spectrum produced by decaying unstable hadrons such as pions and kaons. In addition, for the high-energy electron source Q_{-} , we consider knock-on electrons produced by Coulomb collisions with CR protons (Abraham, Brunstein & Cline 1966). The knock-on electrons contribute somewhat to the continuum emission as bremsstrahlung emission.

To obtain the source term of secondary positrons and electrons $Q_{\pm}(t, E)$, we need to calculate the spectral evolution of CR protons. CR protons are injected from SNRs to molecular clouds in an energy-dependent way (Ohira, Murase & Yamazaki 2010). Moreover, the diffusion escape from molecular clouds should be considered for CR protons above 10 GeV (see Fig. 1). However, we do not need to calculate the precise spectrum of CR protons above 1 GeV because thanks to *AGILE* and *Fermi*, we have already known spectra of CR protons above 1 GeV. That is, we do not need to calculate the spectral evolution due to the diffusion escape for CR protons. On the other hand, we have to calculate the evolution of the spectrum of CR protons below 1 GeV because gamma-ray spectra do not tell us the spectrum of CR protons below 1 GeV. Furthermore, the injection of CR protons is thought to stop when SNR shock collides with molecular clouds (Ohira et al. 2011a), that is, the injection of CR protons stopped of the order of 10^4 yrs ago. Therefore, we assume that CR protons are injected as a delta function in time and an effective steep-spectrum, Q_{CR} , instead of neglecting the diffusion escape

$$Q_{\text{CR}}(t, E) = q_{\text{CR}}(E) \delta(t) , \quad (8)$$

where $q_{\text{CR}}(E)$ is

$$q_{\text{CR}}(E) \propto (E + m_p c^2) \left\{ E (E + 2m_p c^2) \right\}^{-\frac{1+s}{2}} , \quad (9)$$

where m_p is the proton mass. This expression gives an injection term of p^{-s} , where p is the momentum of the CR proton. Observations show that spectra of CR protons have broken power-law forms and the spectral index above the break is $s = 2.7 - 2.9$ except for W44 (OBS). In this Letter, we adopt the single power law with $s = 2.8$ (This assumption

does not affect the flux of the annihilation line significantly). Then, the solution to equation (4) for CR protons, f_{CR} , can be expressed by

$$f_{\text{CR}}(t, E) = \frac{\dot{E}(E_0(t, E))}{\dot{E}(E)} q_{\text{CR}}(E_0(t, E)) . \quad (10)$$

As mentioned in previous section, the cooling of CRs below 1 GeV depends on only the density. Hence, the solution (equation (10)) depends on only nt .

To calculate source terms of secondary electrons and positrons, $Q_{\pm}(t', E)$, in equation (5), we approximately use the present spectrum of CR protons, $f_{\text{CR}}(t, E)$, by changing $Q_{\pm}(t', E)$ into $Q_{\pm}(t, E)$ in equation (5). This is because CR protons (about 1 GeV) producing most positrons do not cool and escape for SNRs observed by *Fermi* and *AGILE*. The solution for the secondary positrons and electrons (equation (5)) depends on only nt below 100 GeV. Hereafter, we use nt as the parameter to describe the system (for example, $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$ for $n = 300 \text{ cm}^{-3}$ and $t = 3 \times 10^4 \text{ yr}$). After the cooling time of CR protons above 1 GeV ($nt > 1.9 \times 10^{15} \text{ cm}^{-3} \text{ s}$), all CRs have already cooled and we do not expect any emission.

In Fig. 2 we show the energy spectra of the CR protons, secondary positrons and electrons given in equations (5) and (10), where $s = 2.8$, $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$. For CR protons (green line), the spectrum below 100 MeV is modified from the initial spectrum $q_{\text{CR}}(E)$ by ionization. The electron spectrum (blue lines) is dominated by knock-on electrons below 10 MeV.

A steady-state solution is obtained by changing E_0 to infinity in equation (5). The steady-state spectrum of positrons below the typical energy of the source term E_t is approximately obtained by using the following approximation.

$$Q_+(E) = q_+ \delta(E - E_t) , \quad (11)$$

where q_+ is the total production number of the secondary positrons per unit time. Then, the steady-state spectrum below E_t is given by

$$f_+(E) = \frac{q_+}{|\dot{E}(E)|} \exp \left(- \int_E^{E_t} \frac{d\epsilon'}{\tau_{a,+} |\dot{E}|} \right) . \quad (12)$$

4 RADIATION SPECTRUM

In this section, we calculate the radiation spectrum from secondary positrons and electrons at $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$. In this case, primary CR electrons are negligible as long as the ratio of primary CR electrons to CR protons is $K_{\text{ep}} < 0.01$ (see Fig. 2). We calculate synchrotron emission, inverse Compton emission with CMB and bremsstrahlung emission from secondary positrons and electrons (Strong, Moskalenko & Reimer 2000), bremsstrahlung emission from CR protons (Schuster & Schlickeiser 2003), and annihilation emission from secondary positrons (e.g. Sizun et al. 2006). Energy spectra of secondary positrons and electrons, obtained from equation (5), are shown in Fig. 2.

When positrons cool to $\sim 10^2 \text{ eV}$, they form positroniums through charge exchange. The production rate of the positroniums, Q_{Ps} , is obtained by

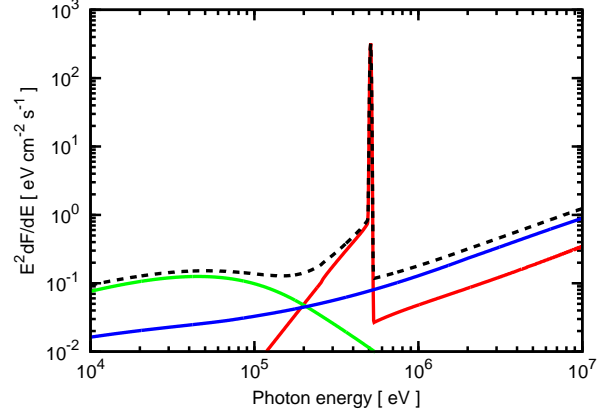


Figure 3. Photon spectrum from an SNR with $F_{>100 \text{ MeV}} = 10^{-6} \text{ photon s}^{-1} \text{ cm}^{-2}$, $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$ and $s = 2.8$. The black dashed line shows the total spectrum. The red, blue and green lines show the annihilation spectrum, the bremsstrahlung spectrum from secondary positrons and electrons, and the bremsstrahlung spectrum from CR protons, respectively.

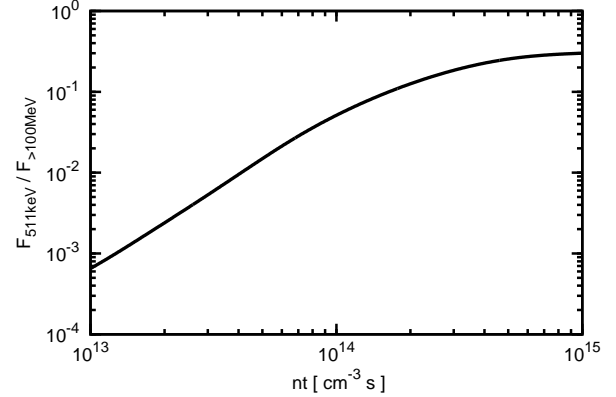


Figure 4. The line shows $F_{511 \text{ keV}} / F_{>100 \text{ MeV}}$ as a function of nt for $s = 2.8$.

$$Q_{\text{Ps}}(t) = |\dot{E}(100 \text{ eV})| f_+(t, 100 \text{ eV}) . \quad (13)$$

One fourth of positroniums decay into two 511 keV photons. Thus the photon flux of the 511 keV line, $F_{511 \text{ keV}}$, is given by

$$F_{511 \text{ keV}}(t) = \frac{Q_{\text{Ps}}(t)}{8\pi d^2} . \quad (14)$$

where d is the source distance. The line width of the annihilation line of positroniums emitted from molecular clouds is 6.4 keV (Guessoum, Jean & Gillard 2005). We here use a Gaussian profile with the 6.4 keV width as the line structure.

Fig. 3 shows the photon spectrum normalized so as to make $F_{>100 \text{ MeV}} = 10^{-6} \text{ photon s}^{-1} \text{ cm}^{-2}$, where $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$ and $s = 2.8$. We again note that this condition is typical for middle-aged SNRs observed by gamma-ray telescopes. Annihilation emission (red line) dominates at around the 511 keV range. It is notable that synchrotron emission and inverse Compton emission with CMB induced by secondary positrons and electrons do not contribute in the energy range of Fig. 3. Moreover, synchrotron emission

by secondary positrons and electrons depends on the magnetic field, the maximum energy of CR protons and the spectral index of CR protons (s). Bremsstrahlung emission of CR protons (green line) also depends on s . Note that bremsstrahlung emission of CR protons can be observed by the future X-ray telescope, NuSTAR (Harrison et al. 2005) and ASTRO-H (Takahashi et al. 2010).

For the estimation of the annihilation line, we can neglect the escape loss as long as $\tau_{\text{cool}} < \tau_d$ for $E < 100$ MeV. Moreover, most positrons are cooled by the ionization loss as long as $B < 1$ mG ($n/300 \text{ cm}^{-3}$)^{1/2}, so that the magnetic field (B), the size of molecular clouds (R_c) and the normalization of the diffusion coefficient (χ) are not important. Hence, the ambiguity of the annihilation line is only nt . Fig. 4 shows the flux ratio, $F_{511 \text{ keV}}/F_{>100 \text{ MeV}}$, as a function of nt , where $s = 2.8$. The ratio does not depend on the number of CRs and the distance. The flux ratio, $F_{511 \text{ keV}}/F_{>100 \text{ MeV}}$, becomes constant after $nt = 2.8 \times 10^{14} \text{ cm}^{-3} \text{ s}$ because almost all positrons have cooled to 100 eV by that time. From Fig. 4 we expect $F_{511 \text{ keV}} \sim 10^{-7} \text{ photon cm}^{-2} \text{ s}^{-1}$ from SNRs with $nt = 10^{14} - 10^{15} \text{ cm}^{-3} \text{ s}$ and with $F_{>100 \text{ MeV}} \sim 10^6 \text{ photon cm}^{-2} \text{ s}^{-1}$. The expected flux of the annihilation line, $F_{511 \text{ keV}}$, can be sufficient for five-years observations of ACT to detect (Boggs et al. 2006). Therefore we can expect to detect the annihilation line of secondary positrons produced by the CR protons in SNRs observed by *AGILE* and *Fermi*.

5 DISCUSSION AND SUMMARY

In this Letter, we have investigated the MeV emission spectrum due to CR protons from SNRs interacting with molecular clouds. We found that for typical middle-aged SNRs observed by *AGILE* and *Fermi*, secondary positrons can cool to an energy sufficient to make positroniums. We calculated annihilation emission of the positrons and other emissions. The expected flux of the annihilation line is sufficient for the future gamma-ray telescope, such as ACT, to detect. Therefore, we propose that annihilation emission from secondary positrons is a important tool as a CR probe. Moreover, synchrotron emission from secondary positrons and electrons, and bremsstrahlung emission from CR protons can be also observed by the future X-ray telescope, NuSTAR (Harrison et al. 2005) and ASTRO-H (Takahashi et al. 2010).

All particles with energies smaller than 1 GeV lose their energy due to ionization, as shown in Fig. 1. Not only the 511 keV line but also the ionization rate is also a probe of CR nuclei (Goto et al. 2008; Indriolo et al. 2010). Becker et al. (2011) proposed that H_2^+ and H_3^+ lime emissions should be observed from molecular clouds if there are many CRs. Low energy CR protons and knock-on electrons might be measured by using atomic lines (Gabriel & Philips 1979; Tatischeff 2003), so that atomic lines also become a probe of CR nuclei. Quantitative estimations will be addressed in future work. Moreover, CR nuclei can produce nuclear excitation lines by inelastic collisions and productions of unstable nuclei (e.g. Nath & Biermann 1994; Tatischeff 2003; Summa, Elsässer & Mannheim 2011). Therefore, CR compositions around SNRs can be also investigated by the nuclear excitation lines. Recent observations and theoretical

studies for CR compositions are also remarkable (Ahn et al. 2010; Ohira & Ioka 2011)

The spectra of secondary positrons and electrons produced by CR protons are different from a single power law because of their cooling and injection spectra (see Fig. 2). The spectra of secondary positrons and electrons below 100 MeV would become harder than the CR proton spectrum around 1 GeV. The number of secondary positrons and electrons can be larger than that of primary CR electrons when the SNR age is larger than about 10 percent of the cooling time of CR protons due to the inelastic collision. Even when the number of the primary CR electrons is larger than that of secondary positrons and electrons, the spectrum is affected by the cooling. These cooling effects of positrons and electrons might be a reason why radio spectra are different from expected from gamma-ray spectra observed by *Fermi* (Uchiyama et al. 2010). However, the radio emission from SNRs may be originated from inside the SNR, but observed gamma rays may be originated from outside the SNR. That is, a different component may produce the radio emission. We may have to build more detailed models to compare the theory and observed data in future. It is an interesting future work to compare between observations and the theory for individual SNRs.

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